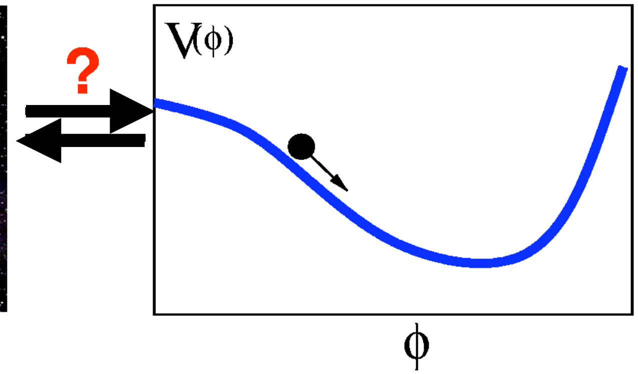
Dark halo densities, substructure, and the primordial power spectrum



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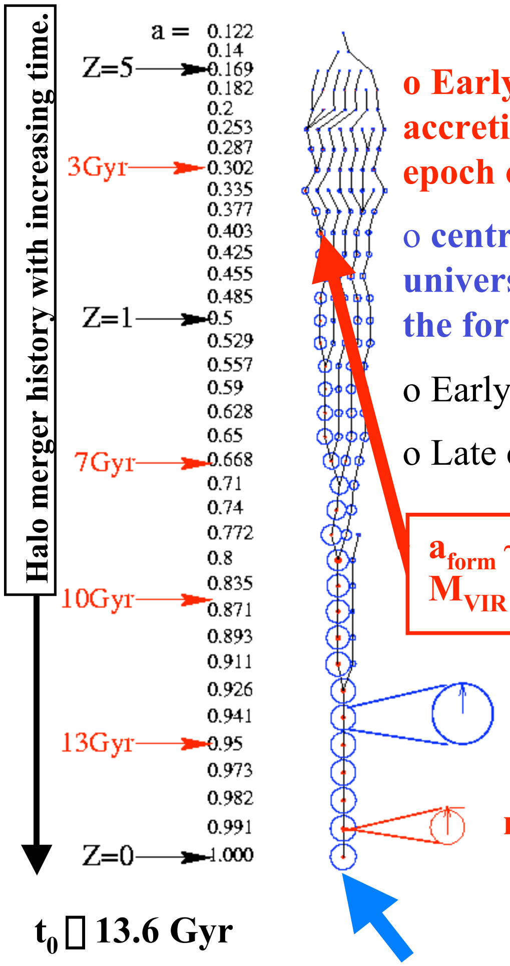
Based on ARZ & Bullock PRD 66, 043003 (astro-ph/0205216), Bullock & ARZ (astro-ph/0207534), and ARZ & Bullock (in prep.)

Dark halo central densities

Density set by mass accretion history



o Early epoch of rapid mass accretion during collapse epoch of central region

o central densities reflect universal density during the formation epoch

o Early collapse → **DENSE**

o Late collapse → **Diffuse**

$a_{form} \sim 0.4$, t~4.2 Gyr
$M_{VIR} \sim 1.2 \times 10^{12}\ M_\odot$

Virial Radius, $R_{VIR} \sim M_v^{1/3}$

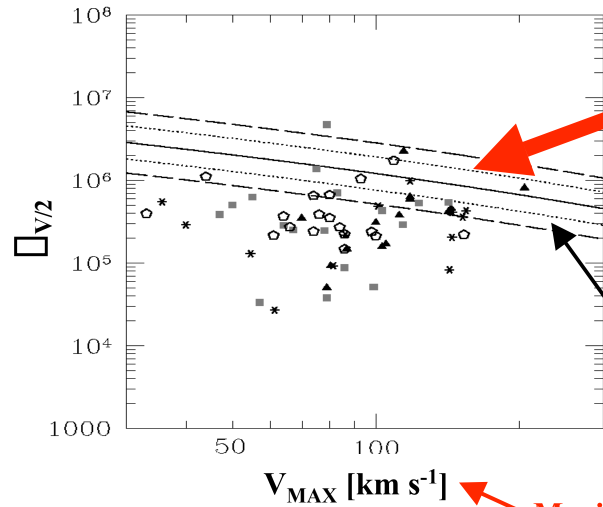
$r_s \sim$ scale radius

$t_0 \approx$ 13.6 Gyr

$4 \times 10^{12}\ M_\odot$ ~ **Milky Way**

•Wechsler, Bullock, Primack, Kravtsov & Dekel 02; Shapiro & Iliev 02; Bullock et al. 01; Eke, Navarro & Steinmetz 01; NFW 95,96,97.

The central density problem



ΛCDM prediction is ~ 6× higher than observed in dark matter-dominated galaxies!!!!

Dashed & dotted lines are expected 1σ, 2σ scatter.

Maximum circular velocity

Definition: $\Delta_{V/2}$ is the mean density, relative to critical, within the radius $r_{V/2}$, where the rotation curve drops to half of its maximum.

$$\Delta_{V/2} \equiv \frac{\bar{\rho}(r < r_{V/2})}{\rho_{CRIT}}$$

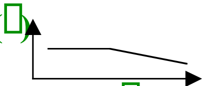
•Note: Integrated density is robustly determined → Need less concentrated halos regardless of the of the "cusp vs. core" issue!!!

•Many ways to quantify density problem: ARZ & Bullock 02; Bullock et al. 01; van den Bosch & Swaters 01 (rotation curves); Debattista & Sellwood 01 (bar braking); Keeton 01(lensing), ...

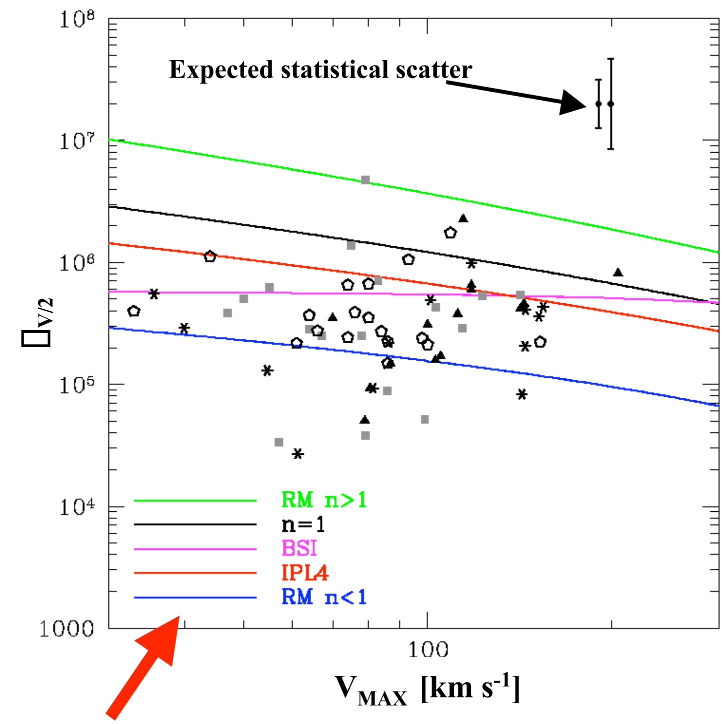
•Observed densities derived from rotation curve data of de Blok et al. 01; de Blok & Bosma 02; and courtesy of R.A. Swaters

Densities and the initial power spectrum

•Inflationary models where a field rolls down its potential must predict some (perhaps very small) deviation from n=1.
•To study the effect of the initial spectrum, we examine the following illustrative examples. All COBE normalized.
n_{COBE}, n_{GALAXY} = effective tilt on COBE and galaxy scales

Model (abbreviation)	n_{COBE}	n_{GALAXY}	'running'	□$_8$
"standard" (n=1) Harrison (70), Zel'dovich(72)	≡1.0	≡1.0	≡ 0.0	□0.95
"chaotic" V(□) = m^2□^{2}/2 Linde (83)	□0.96	□0.95	small	□0.87
"inverted power law" (IPL4) V(□) = V$_0$(1-□□^{4})	□0.94	□0.92	|dn/dlnk|□0.001	□0.83
"running mass" (RM n<1), (RM n>1) V(□)=V$_0$+m^2□^{2}/2 +A□^{2}ln(□/□$_0$) Stewart (97,98), Covi, Lyth & Roszkowski (99), Covi & Lyth (99)	□0.85	□0.79	|dn/dlnk|□0.005	□0.65
	□1.10	□1.09	small	□1.21
"broken scale-invariance" (BSI) Starobinsky (92), Silk et al. (87), Salopek et al. (89), Polarski & Starobinsky (92), Adams et al. (99), Kamionkowski & Liddle (00) V(□)  □	=1.0	=1.0	Break in fluctuation amplitude due to change in slope of V(□) (set break at $M_C \sim 10^{10} h^{-1} M_\odot$)	□0.97

Result:



• Central densities can be reduced to acceptable levels by introducing nonstandard initial spectra.

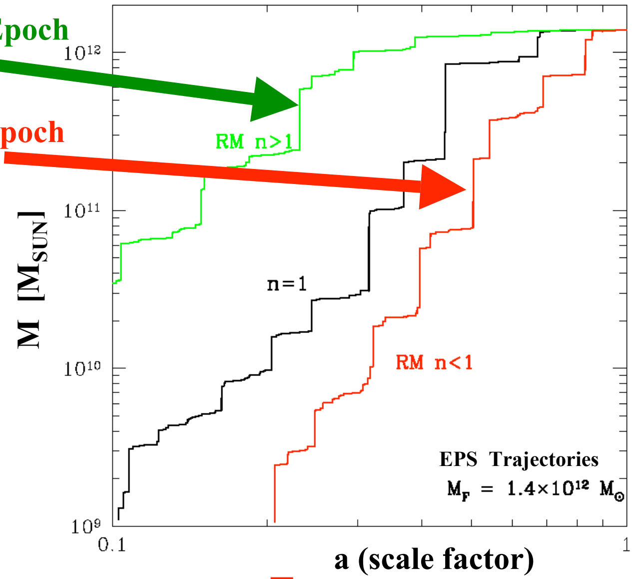
• Concentration as a function of virial mass ($c_{vir} \equiv R_{vir}/r_s$) can be reduced by more than a factor of two !!!

WHY ?? →

Modified mass accretion histories!

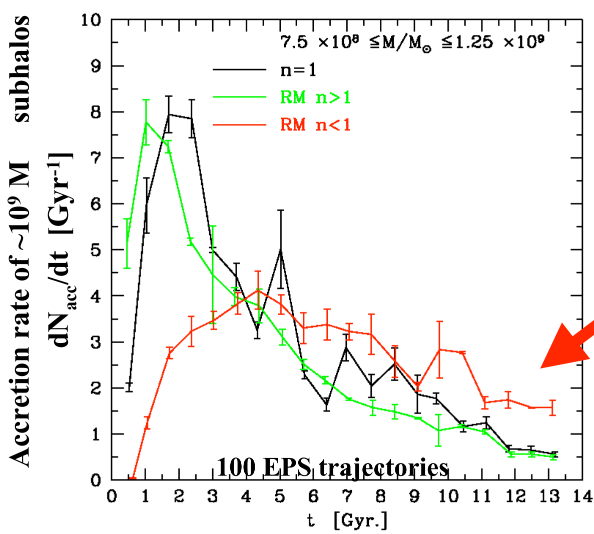
Early Formation Epoch

Late Formation Epoch



• Earlier core mass assembly□ halos are less dense!

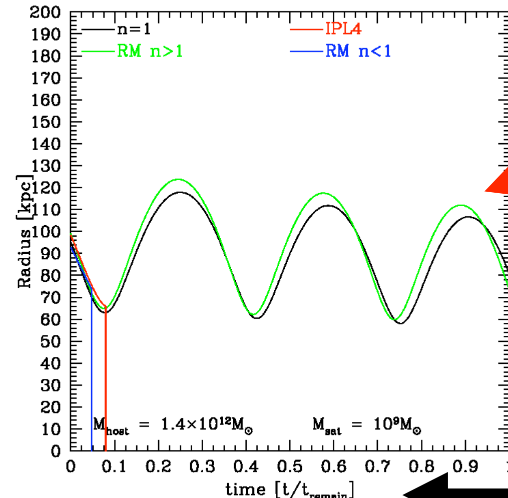
• Subhalos accreted at low redshift □ recent mergers!



Tilted spectrum means more recent accretion events !!!

Lacey & Cole (93); Somerville & Kolatt (99).

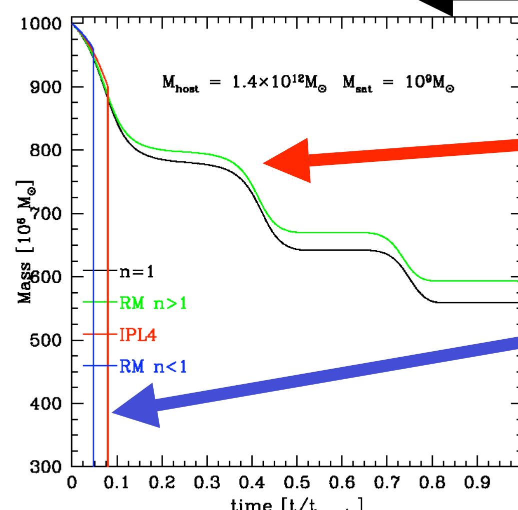
• We can track subhalos after accretion as they are tidally stripped and sink due to dynamical friction.



Orbits decay due to dynamical friction

• Massive objects sink to halo center.

Time normalized to time left subsequent to accretion event.



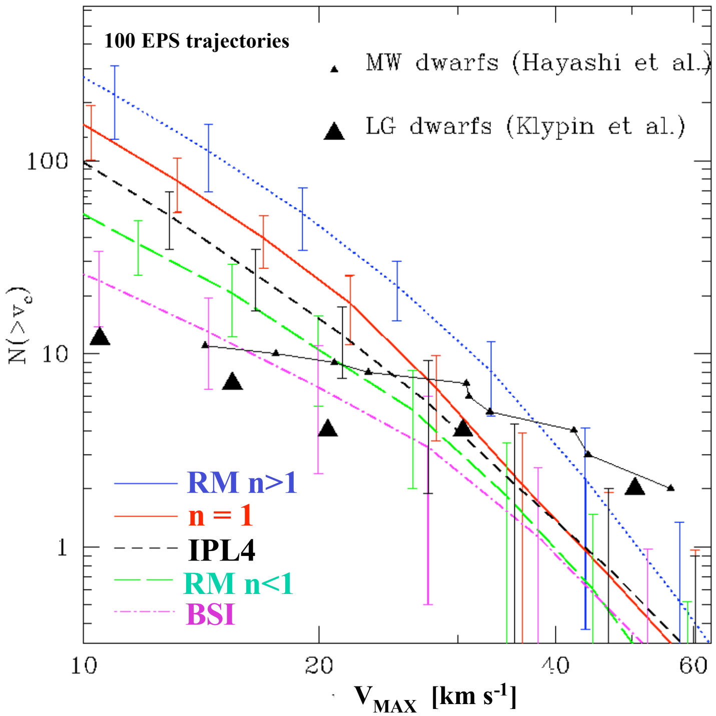
Mass tidally stripped at each pericenter passage.

Less concentrated halos of tilted models are more easily destroyed

Taylor & Babul (01); ARZ & Bullock (02).

The surviving substructure

Dwarf satellites: the velocity function

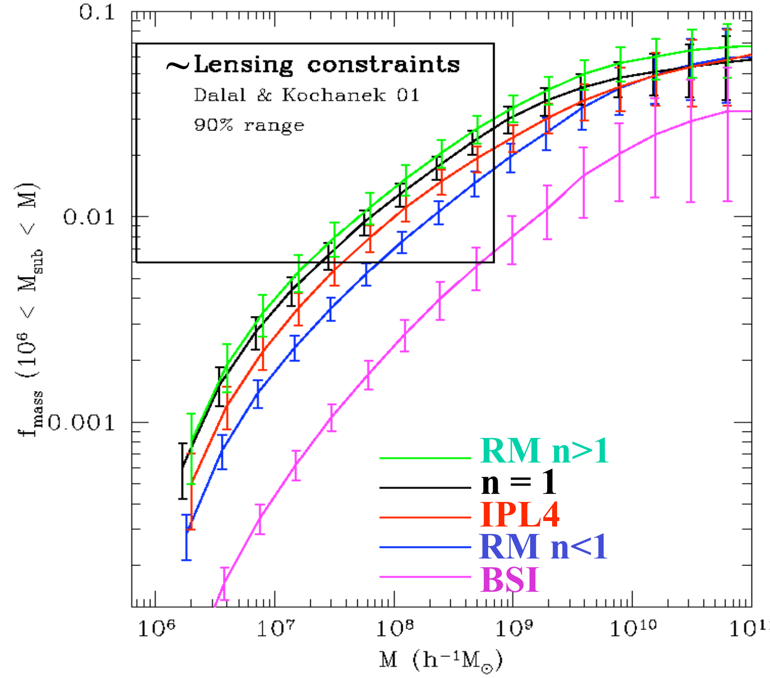


- At fixed mass, less concentrated satellites destroyed.
- Lower concentrations: fixed V larger mass objects that are intrinsically less abundant.

1. ~ 3 fewer satellites at fixed V_{max}
2. Less need for suppression mechanisms like reionization suppression to match data!
3. $z_{reionization}$ ~ 6.5(?) more easily accommodated

Becker, Fan et al. 01; Bullock, Kravtsov & Weinberg 01; Thoul & Weinberg 96

Mass fraction in substructure



- The perturbing effect of substructure in strong lens systems can be used to CDM subhalos, but taking the next step toward constraining cosmology is difficult and questionable.

  [Dalal & Kochanek 01; Metcalf & Madau 01; Keeton 01; Mao & Schneider 98]

- Surviving substructure is not strong function of small scale power if the Dalal & Kochanek bounds on mass fraction in substructure are correct, these measurements do not yet place meaningful constraints on the primordial power spectrum (or on neutrino mass)!

Conclusions & Discussion

1. Moderate, yet observationally acceptable tilts (running is important here too!) lead to galactic halos may provide an acceptable solution to the central density problem. Recent determinations of "low" values of σ_8 (~ 0.6 - 0.75) may point toward this solution.

[Melchiorri & Silk (02); Bahcall (02); Lahav et al. (2dFGRS) (02); Seljak (01); Viana et al. (01)]

2. Does this come at a cost of predicting insufficient substructure?

> **"… lensing implies the need for a mechanism that reduces dark matter densities on kiloparsec scales without erasing structure on smaller scales."**
>
> **- Charles R. Keeton (astro-ph/0112350)**

3. The abundance of substructure is only mildly reduced. The velocity function of dwarf halos is reduced by no more than a factor of 3-4 at small V_{max} (unless we consider broken scale invariant spectra).

4. As a result:

- **The number of dwarf halos will not be <u>underpredicted</u> in light of known mechanisms that suppress star formation moreover, the mild reduction in the number of subhalos may make reionization suppression with fairly low $z_{reionization}$ (~ 6.5) more tenable.** **[Becker, Fan et al. 01; Bullock et al. 01; Klypin et al. 01; Thoul & Weinberg 96]**
- **Lensing measurements do not yet constrain the primordial power spectrum.**

5. The abundance of satellites is not a strong function of initial spectrum because:

- **in tilted models, subhalos are accreted later $\Rightarrow$ less time to be destroyed in galactic gravitational field.**
- **dynamical friction and tidal stripping 'conspire.' Objects that don't lose mass more rapidly sink to the center, where they can be more efficiently stripped of mass.** **[Taylor & Babul 01]**